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METHOD AND APPARATUS FOR
ABIST DIAGNOSTICS

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I N T E R N A T I O N A L B U S I N E S S M A C H I N E S
C O R P O R A T I O N

Title: Method and Apparatus for ABIST Diagnostics

FIELD OF THE INVENTION: This invention relates to integrated chip diagnostics, and particularly to an improvement ABIST diagnostic method and apparatus for use in testing system components, such
5 as SRAM and DRAM devices.

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10 Background:

High speed, density and reliability requirements for computer system applications of static random access memory (SRAM) require efficient and effective test applications to process and manufacture viable components for high end processor products.

15 Manufacturing yield, and ultimately product cost is an integral part of the ability to design, manufacture, and sell computer systems in the marketplace. A key requirement to achieving leading edge technology implementations is the ability to diagnose problems in the design/manufacturing process for early
20 resolution, in a timely fashion, and to lower overall technology cost, prior to product volume ramp-up. Efficient SRAM/DRAM designs stress the manufacturing process capability due to the high device usage (transistor elements) in a given area (smaller memory cell yields higher number of bits per chip), and the high
25 end processor applications demand high memory bit usage. This yields an increased sensitivity to process defects over the accompanying logic, typically, and this drives the need to analyze, understand, and eventually reduce overall process defect density to achieve product yield and cost requirements.

To this end IBM uses integrated self test, and particularly for the memory arrays, the Array Built In Self Test (ABIST) has been employed to provide deterministic test coverage ensuring high quality products. Diagnosis of fails to initial

- 5 manufacturing test and subsequent stress screens are critical to yield diagnostics and product reliability improvement efforts, as they are more realistic indicators than monitor structures. Monitor structures are easier to diagnose, but are only models of the product/process interaction, and are expensive from the
- 10 perspective of area overhead and process productivity.

- Diagnosis of array cell failures currently requires execution of the ABIST algorithm, synchronous to an external test system, during which an off-chip fail indicator is monitored, on a
- 15 cycle-by-cycle basis, to determine at which points in the test the array fails. The external test equipment is used to record the failing cycles, and to repeat the test algorithms stopping "n" cycles prior to each fail, to account for the number of cycles required to "pipe" the fail indicator to an observe point,
- 20 where the failing state of the array data bus can be scanned off-chip for analysis. Given the failing cycles of the ABIST algorithm, one can calculate the expected memory array data for the test and compare to the failing data scanned from the chip. The combination of the calculation of failing memory array data
- 25 out, and the algorithmic calculation from the self test engine state to obtain the memory array address location together provide sufficient information for a logical cell determination of the fail. This requires clocking the array in a synchronous manner with the external test exerciser (tester) and the ability
- 30 to successfully repeat failure on each of multiple passes through the test algorithm.

The technique falls short if the fails are not "hard" repeatable fails. If a fail is on the edge of the point of failure, ("soft"

fails) which sometimes fails or not depending on the conditions at the time of execution, it is difficult to capture and verify. Also, AC defects (defects dependent on the speed/rate at which the algorithm is applied) are not detectable if the exerciser
5 (tester) is not able to apply the test algorithm at the failing cycle time. This process is insufficient for diagnosis of those defects that are not detectable at test frequencies that can be provided by external test equipment, but rather rely on on-chip clock frequency multiplication techniques to multiply tester
10 provided clock signal frequencies to those that meet or exceed the intended application.

This process is workable for low incidents of reliability or line return fails, but is insufficient for line monitoring activity or identification of nonrandom manufacturing defects (such as mask
15 defects, also known as "repeaters") due to the interactive nature of the procedures, and the test hardware and manpower resources required.

Summary of the Invention:

This invention provides a method and apparatus for real time
20 capture of the desired failing memory cell diagnostic information from high speed ABIST testing. This data is obtained for immediate scan-out off-chip at any level of assembly test, such as initial manufacturing wafer test, module test, including system level test, regardless of the clocking methodology.
25 Therefore, combined with current state of the art ABIST techniques, this invention provides in-situ real time ABIST deterministic test cell fail diagnostic information. In addition, the invention provides not only for the data collection of the first failing cell, it can also be programmed to skip up to the
30 "Nth" failing cell and record the subsequent "Nth+1 fail instead.

The invention apparatus takes partial advantage of existing ABIST design hardware required to generate test vectors for array products, by reusing existing address register fields, and supplementing where necessary to provide for complete device
5 under test address fields. These address registers are pipe-lined to provide data synchronous to the existing ABIST fail determination circuitry. In addition, existing ABIST comparison circuitry is used to provide a bit wise fail result vector corresponding to each of the data outs of the memory array or
10 device under test. This fail result vector feeds a unique detect and encode circuit that determines if one and only one array data out failed, and if so, provides an encoded "address" that is concatenated to the memory array address field. Usage of the detect and encode method is proposed here as sufficient to
15 describe failed memory array locations for efficient (minimal hardware apparatus) real time data collection.

The pipe-lined data is then fed into a hold and compare function. This hold portion of the function provides for the "full" fail address field (as defined to be the memory address of the device
20 under test + the failing output encoded address, together sufficient to describe the failing location, or cell, in the memory array) to be stored and held in an LSSD register. The compare function provides for subsequent unique and different failing locations in the memory array to be identified. The hold
25 and compare function is configured to load the first and reload each subsequent unique failing location encountered, decrementing the programmable skip counter at each unique fail encountered, until the skip counter reaches the final "zero" state, or the intended "Nth" fail to be recorded. It is recognized that the
30 primary usage of the function will be to allow the default skip counter of zero thus enabling the first fail to be recorded by the aforementioned apparatus.

These and other improvements are set forth in the following detailed description. For a better understanding of the invention with advantages and features, refer to the description and to the drawings.

5 Description of the Drawings:

FIGURE 1 shows a typical ABIST implementation represented by array system support elements and their configuration.

FIGURE 2 illustrates another variation of an ABIST element configuration with support elements used again, but not

10 restricted to, in support of two dimensional memory array redundancy allocation.

FIGURE 3 illustrates the preferred embodiment of the ABIST diagnostic apparatus element connection for the diagnostic tests herein described

15 FIGURE 4 illustrates that in the preferred embodiment the apparatus employed is composed of three primary elements, a fail trap register, a skip fail counter, and a hold and compare function.

Our detailed description explains the preferred embodiments of
20 our invention, together with advantages and features, by way of example with reference to the drawings.

Detailed Description of the Invention:

As we have noted, this development of our improved method and apparatus for real time capture of the desired failing memory
25 cell diagnostic information from high speed ABIST testing uses the data obtained for immediate scan-out off-chip at any level of assembly test, such as initial manufacturing wafer test, module test, including system level test, regardless of the clocking methodology. Therefore, combined with current state of the art

ABIST techniques, this provides in-situ real time ABIST
deterministic test cell fail diagnostic information. In addition,
the date is collected not only for the data collection of the
first failing cell, it can also be programmed to skip up to the
5 "Nth" failing cell and record the subsequent "Nth+1 fail instead.

By virtue of the described method and apparatus we believe we
have provided an extremely cost effective solution to the problem
of AC (high speed) memory array cell diagnostics for both "hard"
and "soft" defect mechanisms. Given that large on-chip memory
10 macros are the primary semiconductor device yield drivers, they
currently employ built in self test and some form of redundancy
support for overall yield enhancement. By taking advantage of
existing test infrastructure, this adds only a small percentage
overhead, estimated at no more than 15% increase in overall ABIST
15 area.

Data is collected initially and continually for immediate and
continual data collection of manufacturing yield diagnostic
information for every memory macro tested, whether the part
yields or not, and whether or not redundant elements will be used
20 to invoke repair. There is no test time impact, and no
restriction to wafer level test data sites. Every macro, every
part, every environmental test condition or test segment will
have the benefit of diagnostic cell calls as part of the LSSD
scan-out to obtain the manufacturing test results. See IBM
25 Journal of Research and Development, "Boundary-Scan Design
Principles for Efficient LSSD ASIC Testing" by R.W. Bassett et
al., Vol. 34, No. 2/3, Mar/May 1990. The use of existing array
deterministic diagnostics for ABIST would typically be applied
for use with a semiconductor chip which already has the circuits
30 as described by Huott et al. in US Patent 5659441, such as
a semiconductor chip having a VLSI array for storing information
having redundant areas, and an array built-in, on-chip test

system (ABIST) for testing the VLSI array. The existing ABIST uses data input ports, data output ports, and address ports, and includes a data control register for generating and applying deterministic data patterns to the data input ports of said VLSI array. An address control register is provided for generating addresses for application to the chip in coordination with a data control register. A comparator is provided for comparison of data inputted to the data input ports of the VLSI array from the data control register with data outputted from the data output ports of said VLSI array. This comparator includes a failing address function store for retaining failing addresses. A memory array is used for storing a plurality of microcode control vectors, each vector including a data control register field, an address control register field, a microcode pointer control register field and a read/write enable control field; a microcode pointer control register and finite state machine. There are also controls for the address control register, said data control register and said microcode pointer control register which control them in response to a plurality of microcode control vectors. There is also an overflow feedback state for the data control register and address control register. The use of redundancy provides areas for replacing normal functional areas of the VLSI array with the ABIST comparator retaining failing addresses indicating that a hardware error has been detected on power-on of said computer system element. These elements are described in detail in US Patent 5659551 "Programmable computer system element with built-in self test method and apparatus for repair during power-on ", issued August 19, 1997.

In addition, for early life stress testing, burn-in, or extended voltage test, results will include diagnostic cell call information of any fail detected. This will have a significant impact by reducing traditional diagnostic re-test lead time, test equipment resource and manpower, and lead time to schedule and

collect data required to guide Physical Failure Analysis efforts and establish timely problem resolution actions for line control. Subsequent level of assembly test will also see this described benefit.

- 5 The preferred embodiment of our invention will be described herein with relation to existing ABIST implementations, such as those described in patents which are mentioned below and incorporated hereing by reference, including the patents of Dreibelbis et al., US Patent 5961653 entitled "Processor based
- 10 BIST for an embedded memory" issued October 5, 1999, and the patent of Koch et al, US Patent 5535164 for a BIST tester for multiple memories and will further reference this as the ABIST test engine wherein Dreibelbis describes an integrated chip having a DRAM embedded in logic is tested by an in-situ processor
- 15 oriented BIST macro. The BIST is provided with two ROMs, one for storing test instructions and a second, which is scannable, that provides sequencing for the test instructions stored in the first ROM, as well as branching and looping capabilities. The BIST macro has, in addition, a redundancy allocation logic section for
- 20 monitoring failures within the DRAM and for replacing failing word and/or data lines. By stacking the DRAM in 0.5 mb increments up to a 4.0 mb maximum or in 1.0 mb increments up to an 8 mb maximum, all of which are controlled and tested by the BIST macro, a customized chip design with a high level of granularity
- 25 can be achieved and tailored to specific applications within a larger ASIC.

The support for two dimensional redundancy allocation as described by Hedberg and Koch specifically for memory array test

30 is US Patent 5859804 entitled "Method and apparatus for real time two dimensional redundancy allocation" issued January 12, 1999 which should also be and is referenced for two dimensional redundancy allocation. The US Patent 5859804 circuit provided an

array built in self test (ABIST) system disposed on a single semiconductor chip. The chip provided a memory array having a plurality of column lines and a plurality of row lines and at least one redundant column line and at least one redundant row line with cells coupled to the lines at intersections thereof. This patent thus described a method and apparatus provided in an array built in self test (ABIST) environment formed on the semiconductor chip having an array of memory cells arranged in columns and rows and column and row redundant lines which includes testing the array along the columns to identify a given number of faulty cells in each of the columns, storing the column addresses having the given number of faulty cells in first registers, further testing the array along the columns or rows to identify any additional faulty cells while masking the cells having the stored column addresses and storing the row addresses having the faulty cell in second registers until all of the second registers store row addresses, and after all of the second registers store row addresses, continue testing the array while masking the cells having the stored column or row addresses and storing the column addresses of any remaining additional faulty cell in any unused register of the first registers.

The first level of description of the preferred embodiment of the herein proposed method and apparatus are block level diagrams showing the major components of an overall ABIST system. Figure 3 will show the appurtenant structure of the preferred embodiment.

Figure 1 shows a typical ABIST implementation represented by array system support elements and their configuration. The redundancy allocation support described herein is, but not restricted to, two dimensional in reference to the row and column addressing within the structure of the memory array under test. There may exist a plurality of redundant row and column elements

thus supported by the Redundancy Support Registers. The self test engine provides the deterministic array test patterns. The compare function has as its inputs, the expected data vector and the memory array outputs. It provides an overall pass/fail result signal which is used in combination with the gating controls from the self test engine to control the redundancy support registers in establishing real time redundancy allocation.

Figure 2. below, shows another variation of a ABIST element configuration with support elements used again, but not restricted to, in support of two dimensional memory array redundancy allocation. The exception here, is that there may exist a plurality of row and what will be referred to as column group elements within the memory array structure. These column group elements are not selected by memory array column addressing alone, but instead coincide with a data input/output element in whole or in part.

In this art, one of the redundant/repairable element dimensions correspond to an array I/O in whole or in part. The compare element no longer compresses the test result to a single pass/fail signal, but instead provides individual result signals for each memory array data-out. The Detect/Encode circuit element is thus employed to determine memory array fail repair-ability, first by signaling that one and only one repairable element is failing and then providing an encoded representation, or "effective" address to be processed by the two dimensional redundancy support register. Again, not all memory array addressing bits may be needed by the redundant element allocation register, only those sufficient to uniquely describe/address the redundant element invocation.

Figure 3. illustrates the preferred embodiment of the ABIST diagnostic apparatus element connection for the diagnostic tests

herein described. Note shall be made that in typical support of redundancy allocation, not all memory array addressing bits may be needed. For the purposes of this embodiment, all memory addressing bits are brought to the Diagnostic apparatus. Second, 5 the Redundancy Support Register, in this preferred embodiment, is, but not restricted to, providing two dimensional redundancy support of the memory device under test.

Thus the diagnostic register is not intrusive in existing Abist design methodologies. As can be seen, its function is parallel 10 and independent of the remaining Abist elements. For applications different than this described preferred embodiment, additional elements of the detect and encode element can be brought out of the existing ABIST path if not needed, and used solely for the diagnostic register, slightly increasing the 15 overhead area. In fact, this method and apparatus can be applied even when no redundancy support is required. This will in practical situations be unlikely, since the large array macros drive both redundancy applications for yield improvement, and will gain the most from yield diagnostics using this method, 20 whereas the smaller macros typically without yield focus, will not derive as much benefit from targeted diagnostic activity.

The method and apparatus for the proposed "diagnostic register" will now be described in more detail. There are two inputs to the 25 apparatus, namely an overall validated fail signal from the ABIST compare function, and the address buss comprised of memory array address signals concatenated with the encoded data-out address of the memory array. Any single cell fail occurring within the memory array is thereby uniquely described in a minimally encoded 30 address. Multiple cell fails spanning more than one, or numerous, observed data bits are encoded to an all "1"s state in the encoded data out address field. The positive attributes of the encoding methodology will be discussed later in comparison to

other available or potential solutions to the problem herein stated, and the potential restrictions of the methodology will be summarily resolved in light of the physical limitations of failure analysis itself.

5

Figure 4 shows the ABIST diagnostic apparatus that in the preferred embodiment is composed of three primary elements, a fail trap register, a skip fail counter, and a hold and compare function. The first review will be of circuit function with the skip counter initialized to zero, or what will be referred to as "record first fail" mode, and then with non-zero values of the skip counter to "record $N^{th}+1$ fail". "Record first fail" is considered the default or base function of the method and apparatus. The initial state of all registers is defined to be "0", and is obtained through scan initialization of the LSSD registers in the preferred embodiment.

The skip counter output labeled "count state" is at "0" when the counter bits count down to the all "0" state or are pre-initialized to "0", sensitizing gate **a2**. The address inputs are usually advancing during the course of memory testing, and will at the occurrence of any fail, by definition of including the encoded fail address of the memory array data bit, a mismatch condition will exist. Gate **a1** is thus sensitized to the Fail Signal input pin. Given no fails (yet) from the ABIST compare during memory test, the Fail Signal input is at "0", desensitizing gates **i1** and **o2**, keeping gate **o2** at a "1" state. If the Fail Signal input stays at "0", then the "0" value is maintained in both the fail trap register and the hold and compare registers. Thus, as soon as the Fail Signal input goes to "1", then the hold and compare register multiplexors will be redirected to provide the fail address as new data to the registers themselves. On the next clock event, the fail trap register will set to the "1" state. Simultaneously the hold and

compare registers will set with the failing address information. Now the fail trap register controls the hold and compare multiplexors in the data hold state, such that for all subsequent clock cycles, the first fail address data is held, until the data
5 is retrieved via the LSSD scan port of the register latches.

When the skip counter is initialized to a non zero state, then its function is to count down from the pre-initialized state, whereby its output, count state, will be "1" until the zero state of the down counter is reached. The non-zero state of the skip
10 counter therefore blocks the fail input signal from reaching the fail trap register through gate a2. This mode is held until the intended $N^{th}+1$ fail point is reached, when the skip counter reaches the zero state, operation is as described for the above pre-initialization to "0" state. Operation of the hold and
15 compare register is such that the address of each fail is loaded. Any subsequent fail is compared against the stored failing address, and only unique and new failing addresses will be counted by decrementing the skip counter, and reloading the new address into the hold and compare register. This is accomplished
20 by the mismatch signal line that allows sensitization of gates a1 only when the new fail address is different than the last fail encountered. The hold and compare register structure is made up of an LSSD register as wide as the number of memory address and encoded address bits in total. Each register bit input is
25 multiplexed between either the register bit itself in hold mode, or new address data when the hold signal line is "0". The address input is connected to the multiplexor input as just described, and also one side of an exclusive-or (compare function) with the register bit itself. Therefore each bit of the
30 entire address field is compared with the contents of the hold register on a bit by bit basis. The outputs of the exclusive-ors are logically OR'ed to form an overall mis-compare result. Multiple occurrences of the same fail in the memory array are

thereby precluded from advancing the skip counter. The skip counter is implemented as a binary down counter that will advance from the preprogrammed state on each occurrence of the fail signal and a unique value of the failing address field through gate a1, and the next occurrence of a clock signal.

This method and apparatus allows for real time collection of the first failing memory array cell, and with additional initialization programming of up to the $N^{th}+1$ failing cell. This capability of in-situ collection of cell diagnostic data is provided with minimal on-chip hardware apparatus, and no impact to test time, throughput, or external test hardware resource. As was described in the problem solved description statement, this not only reduces resource and expensive re-test effort to gather this information in a traditional manner, it provides for collection of this data at levels of assembly and during high speed on product clock generation driven test that has been effectively prohibited by prior or current art to date. In addition, this data is now provided during initial wafer manufacturing final test which provides significant yield monitoring capability never provided at such low cost (or any cost) in current or prior art.

The advantage of this proposal is such that although seemingly straightforward in some ways, the unique application of a detect and encode circuit restricting encoded states to a single bit of the entire field as being the sufficient case, allows for the minimal number of states required to be encoded to be equal to the number of data-out bits +1 (multiple fail state). This represents a significant reduction in the number of hardware register bits to store effective fail information. This taken in context of today's high speed applications, the ABIST

implementations utilize the same pipeline and performance techniques applied to system design. This exacerbates the hardware requirements necessary to synchronize a brute force data collection of output data from large memory array designs. The
5 preferred embodiment described herein effectively 'piggybacks' onto existing pipeline data structures in place to support redundancy allocation with minimal expansion to support storage of the full memory addressing buss, but not to the pipeline depths required for the current art.

10 In terms of traditional diagnostic requirements that all failing data outputs need be required for diagnostic data collection, although possibly providing comfort, the information is usually not taken advantage of. This claim is made in context of physical failure analysis techniques that require a single defect
15 to be targeted due to the investigative and destructive nature of mechanically unlayering to reach measurable and quantifiable determinants of failure mechanisms. If the defect isolation is to a peripheral circuit within the memory array causing all outputs to fail, then individual array data-out fail information is not
20 specific, and the peripheral circuit diagnostic information is then solely available within the address field that is stored. More importantly, since it is claimed that this method and apparatus provides immediate diagnostic information for early life stress activity, then the largest number of failure
25 mechanisms are usually singular failures of individual cells in the memory cell array. This method provides clear advantage in this area for recording the most prevalent failure mechanism.

One of the possible on-chip alternatives to the above method and apparatus which has been considered during our own development
30 would use a straightforward pipeline of the full address buss and the full data output buss of the memory array under test up to the point of synchronization with the ABIST determination of a

fail. After our analysis we determined that this alternative requires more hardware, and in some applications could result in hundreds of additional registers to store the output data necessary, to just store the first fail information, for one
5 instance of an array macro. The method and apparatus described as our preferred embodiment has definitive benefit over this alternative.

A second alternative proposal which has been considered for resolving the requirements of diagnostic data collection was to
10 provide an additional copy of the memory array macro on-chip, and to reconfigure ABIST to test the target memory while storing the bit by bit compare results into the "spare" memory macro. Then at some point, another macro becomes the target, and the previously successfully tested target becomes the new data
15 collection/storage device. This second alternative proposal is theoretically viable but we believe it would add additional complexity and area impacts on chip as compared to the preferred embodiment.

A third alternative to the preferred embodiment which has been
20 considered is a alternative which would provide extensive on product clock generation control circuitry to the chip to be tested, whereby the effective number of on product generated clock cycles can be counted and specifically controlled such that a more traditional approach to diagnostic data collection can be
25 implemented. We believe that this is also a valid and workable approach, even though it is not our preferred embodiment because when such circuitry resides on chip for purposes of system control and it can also be used for memory array cell diagnostic activity, although again we do not consider this our preferred
30 embodiment because it does involve more tedious and interactive data collection algorithms to achieve comparable results. If this circuitry, design complexity, and intrusion into the basic

clocking methodology of the chip infrastructure is required for test support, then, the design and usage resource requirements (both hardware and manpower) will normally preclude the design benefit obtained by the third alternative.

5

The application of our method and apparatus is particularly useful in system devices related to high speed processing of data, and can be implemented in devices such as used for cache memory ABIST for high speed processors, including double processor chips where
10 elements are divided into two smaller chips which can be separately tested for improvements in yield and cost, as well as for other memory units and array designs used in complex logic. The design can enable improvements in implementation of complex
15 logic-DRAM, SDRAM, low power technologies, and unique packaging alternatives, and enable processor speed and cost improvements in addition to those obtained by cycle time improvements due to technology scaling.

While the preferred embodiment to the invention has been
20 described, it will be understood that those skilled in the art, both now and in the future, may make various improvements and enhancements which fall within the scope of the claims which follow. These claims should be construed to maintain the proper protection for the invention first described.